Energy Optimality in Novel Movement: Sideways Walking

An Honors Thesis

By

Matthew L. Handford

Undergraduate Program in Department of Mechanical / Aerospace Engineering

The Ohio State University

November 2012

Honors Research Committee:

Manoj Srinivasan, Advisor

Rob Siston

Abstract

The theory of energy optimality states that humans naturally move in a manner that minimizes the energy that their bodies use. This theory has been shown to be approximately true for natural gaits but it has not been tested on many unnatural gaits. To test if this theory would work on novel gaits, we conducted an experiment to compare people's natural preferred speed to their energy optimal speed as they walked sideways. Subjects were asked to choose a comfortable speed using while walking sideways which was then recorded as the preferred velocity. Then, using a portable metabolic measurement system (the Oxycon Mobile VO2 device), their metabolic energy usage was recorded at a variety of speeds. Using this data, energy optimal velocities were found and compared with preferred velocities. While these quantities didn't match exactly, a person's preferred speed could be predicted by the population's optimal speed with an average absolute error of 0.117 m/s. With the caveat that the subject pool was small with high data variability, the mean optimal speed (0.592 m/s) differed from the preferred speeds by only about an average of 0.041 m/s. In future experimentation, we hope to investigate the effects of perception and prior experience and the length of time it takes to reach the energy optimal speed with the subjects' natural movement.

Acknowledgements

This experiment has been over a year in the making and I could never have done it without the support of my professors, fellow students, family and my friends. I want to start by thanking my advisor Dr. Manoj Srinivasan. Throughout this entire project, he was there providing guidance and posing questions that really aided my research. I'd also like to thank the other members of my lab for their support and for showing me the ropes in the lab. Specifically, I'd like to acknowledge Yang Wang for his help with the motion capture software and Geoff Brown for teaching me how to work with the Oxycon Mobile.

I would also like to acknowledge Dr. Rob Siston and my classmates from ME 783H and ME 4999H. This thesis and the presentation for my defense were greatly improved by their feedback in and out of the classroom. The questions, insight, and even purposeful interruptions in class helped me to become so much more comfortable talking to people about what I do. All of your help has been invaluable.

Finally, I would like to thank my family and friends. Throughout this entire process your support and encouragement has been greatly appreciated. Furthermore, I'd like to thank them for putting up with my long hours in the lab and at the computer as I completed this experiment.

Contents

Figures

Tables

1. Introduction

The focus of this thesis is to study how energy influences human locomotion while using an unnatural gait. Humans have around 50 muscles in each leg [1], which are arranged in a way that allows us to move in numerous ways. The flexibility of movement in human legs is expressed, for instance, through the different styles of dance that have existed throughout the ages and humorously through TV sketches such as "The Ministry of Silly Walks" performed in Monty Python's Flying Circus. However, when humans go from point A to point B, they tend to just choose one of two gaits: walking and running. Furthermore, humans tend to use these gaits with similar attributes like walking speed. One of the hypotheses for explaining why humans move the way they do is known as **energy optimality** [2]. This hypothesis states that when completing an action, animals and humans alike will automatically attempt to do so with minimal effort. In the case of locomotion this means that humans naturally minimize our metabolic energy over the distance to be traveled. This thesis explores the applicability of energy optimality in novel unnatural human movements such as sideways walking.

1.1 Past Research

Evidence for energy optimality has been found in many different studies [2,3,4,5,6] in the past including one performed by Ralston [3]. In this study, Ralston measured the metabolic energy usage ($\dot{E}_w$) of multiple subjects as a function of speed and then combined that data with data from other experiments performed in the past. Plotting this energy data against the subjects' velocity (v) squared produced a linear relationship as shown in Equation 1. Thus it is possible to estimate a person's $\dot{E}_w$.

$$\dot{E}_w = 29 + 0.0053v^2 \;\; cal/min/kg \tag{1}$$

Having obtained the energy-speed relationship, this study compared the energy optimal velocity and the **preferred speed** of the subjects who participated in the experiment. Preferred speed refers to the speed that is chosen by the subject without any constraints forced on them by the investigator. Ralston recorded this preferred speed by asking subjects to walk at a comfortable speed. For one such subject, the preferred speed was 73 meters/min (1.22m/s). In order to find the **energy optimal speed**, that is the speed that minimizes the subject's metabolic energy per unit of distance (E_m), Equation (1) was divided by the velocity to produce an equation, which related velocity to E_m as shown below:

$$E_m = \frac{29}{v} + 0.0053v \quad cal/meter/kg \tag{2}$$

Using this function, the minimum E_m was found at a velocity of 74 meters/min (1.23m/s). Thus, the energy optimal speed and the natural speed of this particular subject were different by only 1.4%, which lends significant evidence to the theory of energy optimality [3].

Other studies have used similar strategies while observing step width [4], running [5], step-frequency, and step length [6]. Each of these studies showed evidence that energy optimality can be a reasonable predictor for a person's natural gait.

1.2 Unnatural Gait

While energy optimality is known to be a good predictor of human locomotion, almost all previous studies on this topic have used natural gaits such as walking and running. By studying unnatural gaits, we can better determine the limitations of the theory and whether or not it could be used as a predictive tool when studying altered gaits associated with injuries or prostheses.

Also, if a person does not use the most energy optimal gait the first time they use a new gait, it could be interesting to study how that person's energy usage changes over time.

In this thesis we observe healthy subjects as they use a novel gait that has been assigned to them. Specifically, we studied a sideways walking gait. The sideways walking gait was selected because it was significantly unnatural, repeatable, easily learned, and safe.

1.3 Variables of a Gait

When studying human gaits, there are many variables that can be used to describe the gait. Three commonly observed variables are velocity, step-frequency, and step-length. These three variables are not independent of one another in that any one of them can be described as a function of the other two. It is also important to note that depending on which of these variables is constrained, the minimum on the metabolic energy curve may be shifted [5]. In this thesis we focus on the optimality of preferred speed and do not constrain step-length or frequency.

1.4 Measuring Energy Costs

The theory of energy optimality is based on minimizing metabolic energy expenditure and therefore it is necessary to measure this quantity in test subjects. However, metabolic energy cannot be recorded directly. This means that, in order to determine the rate a subject is using energy; related variables must be measured directly so that metabolic energy can be calculated. There are multiple methods for finding metabolic energy, such as through heart rate or ventilation [7]. But these methods can be unreliable and difficult to verify. Another strategy that has been shown to be reliable is to record subjects rate of oxygen inhalation ($\dot{V}_{O_2}$) and the rate of carbon dioxide ($\dot{V}_{CO_2}$) expiration as they breath. We use this technique for estimating metabolic costs.

1.5 Outline of the Thesis

In Chapter 2 of this thesis, I discuss the initial testing that was performed; including gait selection and safety testing. Then I show the methodology used to gather data from test subjects and the precautions taken to ensure the data was usable and comparable between tests. In Chapter 3, I display the results of each of the tests for the subjects individually and also for the test subject population as a whole. Finally, in Chapter 4, I discuss the results and what it means for the theory of energy optimality in human locomotion.

2. Testing Procedure

2.1 Overview

In order to test the interaction between energy and human locomotion, I used a protocol similar to that used by Ralston [3]. I first test subjects as they used a specified sideways gait without restricting their velocity, step-frequency, or step-length so that they would use the gait "comfortably." Then I record their metabolic energy usage as their gait was altered. These tests produce a relationship between metabolic energy and the altered variable. From this relationship the optimal gait is found and compared with the preferred gait of the subject. From these results, I determine if there is any correlation between the preferred gaits and the energy optimal gaits. For this experiment I use speed as the altered variable.

2.2 Possible walking gaits

I considered two different types of gaits for possible use in the experiment: planar and non-planar sideways gaits. The planar gait, which we called a "shuffle," is shown in Figure 1. This gait requires the test subjects to keep their hips parallel to their direction of travel at all times. As the subjects are walking towards their right side, they extend their right foot in their direction of travel and plant it before lifting their left leg and bringing it towards the right. Thus the person alternates between a straight standing position and a wide stance position.

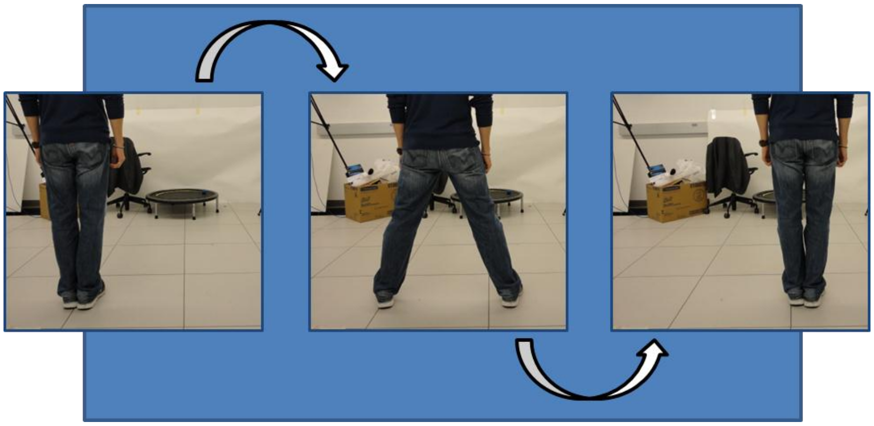

Figure 1: Stages of the planer "Shuffle" gait

The non-planar sideways walking gait which we called a "cross-over" gait is shown in Figure 2. In this gait, the subjects rotate their hips slightly during the gait, and instead of bringing the left foot to a standing position as they would in the shuffle, they would cross their left foot passed their right either from behind or in front of the right foot. This means the non-planar gait could also be divided into two subcategories. The subject can cross their foot either in front or behind for the entire trial (cross-over), or switch between crossing in front and behind with each step (the alternating cross-over).

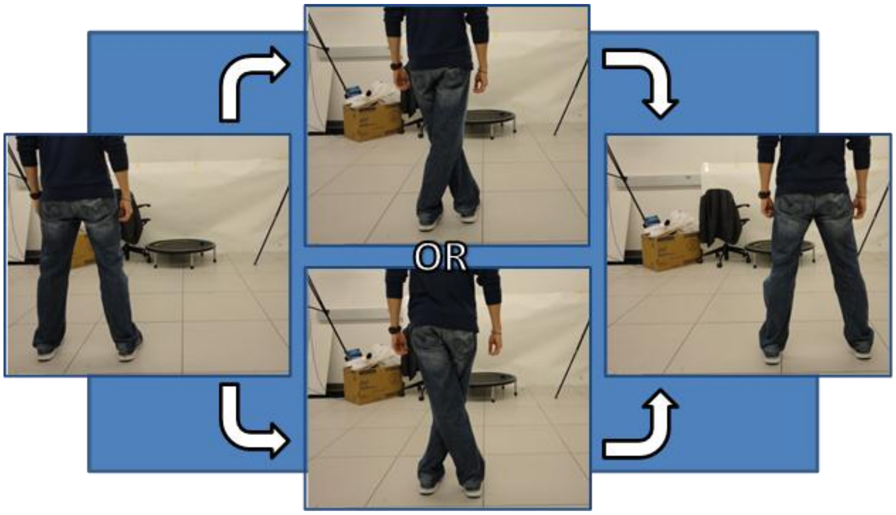

Figure 2: Stages of the non-planer "Cross-Over" gait

2.2 Pilot Testing for Standard Gait

Before finishing the protocol, I examined the shuffle gait and the three variants of the cross-over gait, using a treadmill and marker based motion-capture system for safety and ease of performance. I found the shuffle gait to be safe but tiring. It was observed that while moving to the right most of the work was done by the left leg. This asymmetry made it substantially different from forward walking. The cross-over gaits were found to be less strenuous than the shuffle gait at lower speeds but required significant effort at higher speeds since they involved constantly crossing and uncrossing the subjects' legs. Therefore, the shuffle gait was selected for subject trials. With the gait selected, I conducted further tests and decided to use a speed range of 0.1-0.9 m/s for this gait, based on subject fatigue and coordination.

2.4 Testing Methodology

The protocol was approved by the Ohio State University's Institutional Review Board (IRB) and subjects gave informed consent before any experiments. The experiment consisted of three parts: two used to observe at the subjects preferred gait without constraining speed at the beginning and end of the experiment and one in the middle to observe their metabolic energy with their speed constrained.

2.4.1 Natural Preferred Speed Test

The first stage of the test took place in a hallway and was used to find the subjects natural preferred speed. During this part, no data was taken related to the subjects' energy usage but the subjects were still required to wear a $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ measurement device which would be used in the second portion of the test so that they could get used to the weight of the system and breathing through the mask. Once fitted with the apparatus, a 100 ft distance was measured in a hallway and markers placed at both ends. The subjects were then instructed in the proper motion for the shuffle gait and were asked to walk sideways to the far marker and back again without stopping at whatever pace they found to be comfortable. This meant that the subjects were shuffling for 100ft with their right foot in front and 100 ft with their left foot in front for a total of 200ft. This task was performed as four separate trials and each were timed with a stopwatch. Using this data, I calculated a speed from each of these runs and average them to find the subjects natural preferred speed.

2.4.2 Energy Curve Test

Once the natural preferred speed test was finished, the second stage was started with the goal of developing an energy-velocity curve for the subject. To start this portion of the test, the subjects were asked for basic information including; name, age, gender, height, and weight. Each subject was then fitted with a $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ measurement device from Oxycon Mobile. The Oxycon Mobile was chosen because it is capable of measuring very low ventilation associated with humans at rest or under low physical stress. The system consists of a mask, a small backpack that housed a series of sensors, and a transmitter to send the data to a computer to record the data. Using the data recorded by this device, it is possible to calculate metabolic energy rate using Equation 3 shown below [7].

$$\dot{E}_w = 16.58\dot{V}_{O_2} + 4.51\dot{V}_{CO_2} \tag{3}$$

The subjects were then asked to shuffle on a treadmill at up to ten different speeds from 0.1 to 1m/s. with the top speed depending on the physical capabilities of the subject. Due to complications with our treadmill equipment in the lab, I had to switch to a different treadmill for the majority of the subjects. Because this new treadmill measured speed using English units and had a minimum speed of 0.5 mph, the procedure was changed to 8 speeds from 0.5 to 2.0 mph.

At each of these speeds, the subjects were asked to shuffle, with their choice of foot in front, for six minutes. This allowed for the three minutes in which their $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ could reach a steady state value, and three minutes in which the steady state value could be recorded.

2.4.3 Learned Preferred Speed Test

At the end of the treadmill trials, I repeated the hallway **preferred walking speed** experiment so as to observe any difference between the subjects' preferred speed at the beginning of the test and their speed at the end. This is important because it shows how a person's preferences change after using a gait for an extended period of time. The idea of this was to view a learned preferred speed but after observing certain trends among early tests, which will be described later in this document (Section 3.1), later subjects were asked to walk on the treadmill for 3 minutes at a slower speed before moving back into the hallway.

2.5 Subject Population

In recruiting test subjects, I looked for healthy adults who had the ability to perform the required gait for the protocol duration and without relevant health issues. Also for these tests, no children or pregnant women were used as subjects due to ethical issues associated with these populations. The physical attributes of the 6 subjects tested are shown in Table 1.

Table 1: Subject physical attributes

Subject #	Age (years)	Gender	Height (cm)	Weight (kg)
1	22	M	175.3	95.7
2	50	F	175.3	65.8
3	52	M	180.3	86.2
4	20	F	162.6	59
5	22	F	165.1	64.4
6	22	M	177.8	78.9

2.6 Data Processing

Once gathered, the data was processed using MATLAB. Since this experiment dealt with a human population, it was likely that I would see a variation between the results of each subject. While this difference can be normalized slightly by dividing all $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ readings by the subjects' weight, this would not account for all of the differences between each subject. Therefore, I decided to compare the results of the subjects to themselves and also to the entire subject population. Using this method, it would be possible to determine correlations between the subjects' preferred velocities, their personal energy optimal velocities, and population energy optimal velocity.

3. Results and Data

3.1 Subject Hallway Data

Displayed in Table 2 are the results from the two preferred speed tests. This table shows the average speed of the four trials performed in the hallway during stages one and three of the experiment for each subject.

Table 2: Initial and post-treadmill preferred speed data comparison

Subject #	Initial Preferred Speed (m/s)	Post Treadmill Preferred Speed (m/s)	Speed Difference (m/s)	% Difference
1	0.687	0.702	0.015	2.25%
2	0.789	0.903	0.114	14.40%
3	0.626	0.726	0.100	15.91%
4	0.499	0.560	0.061	12.21%
5	0.397	0.517	0.120	30.15%
6	0.501	0.569	0.067	13.41%
Average Difference			**0.079**	**14.72%**

From this data it can be seen that every subject increased in speed between the first and second hallway tests. As described in a previous section, the test was altered to see if a difference could be observed but this change seemed to have no effect on the data. While this increase was minimal in subject one, most subjects showed a greater than 12% increase in speed with a maximum increase of over 30%. Another interesting result observed in this data is that Subject 2 appeared to have an abnormally high preferred speed compared to the other subjects. Since this speed was near the limits of the testing procedure, the subject was asked to perform another hallway test at a later date. During this final hallway test, it was observed that the subject was using a different gait that she referred to as a "basketball sprint." The subject was used to this similar gait that she generally used in her workout routine. After correcting the gait, her preferred speed decreased to 0.75 m/s.

3.2 Treadmill Data

The Oxycon Mobile was used to determine the amount of $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ for each breath as the subjects walked at each of the predetermined speeds during the treadmill experiment. A sample plot of this data for Subject 3 can be seen in Figure 3. From this data, we see that the $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ increase as a function of the subject's velocity.

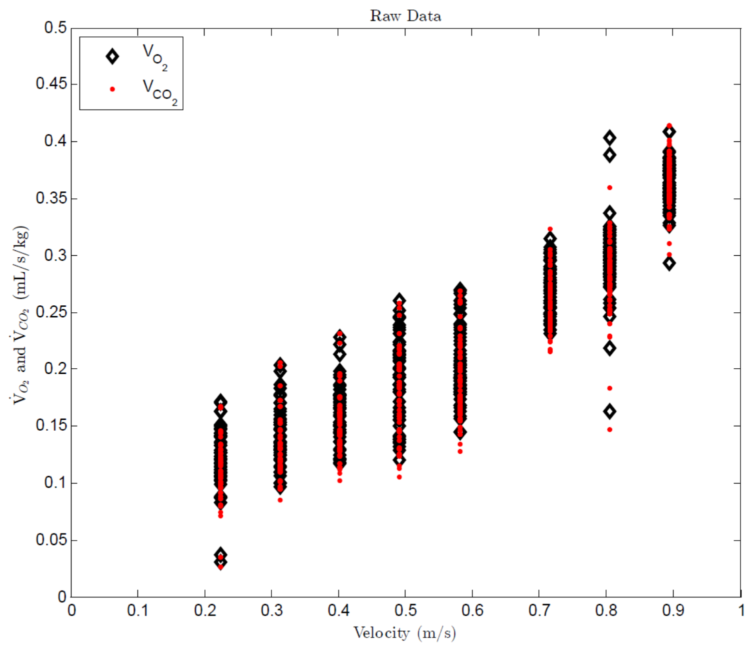

Figure 3: Raw Data from treadmill testing for one subject

3.2.1 Data Quality Checks

To ensure the quality of the $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ data, multiple tests were performed. The first test performed was to look at the respiratory exchange ratio (RER) of the subjects during their trials recorded by the VO2. RER is defined as the ratio of carbon dioxide exhaled to oxygen inhaled in one breath. During mild physical activity associated with low speed locomotion, the average human should have an RER value of around 0.85. This will increase with more intense physical activity and should remain under a value of 1.0 except during extreme physical activity. An RER of 1.0 can only be reached if the subjects are at the anaerobic threshold or hyperventilating. Therefore, if an RER of 1.0 is observed during the test, it shows that the subject is not breathing naturally and the data might be slightly altered. So, the subjects' RER data was averaged over each trial and over the entire treadmill test to determine if unnatural breathing could be a source of error. For every subject tested, it was found that the average RER remained below 1.0 for the majority of trials and no subject had a test average RER over 1.0. A sample plot displaying the RER values for Subject 3 can be seen in Figure 4. The error bars displayed are a 95% confidence interval.

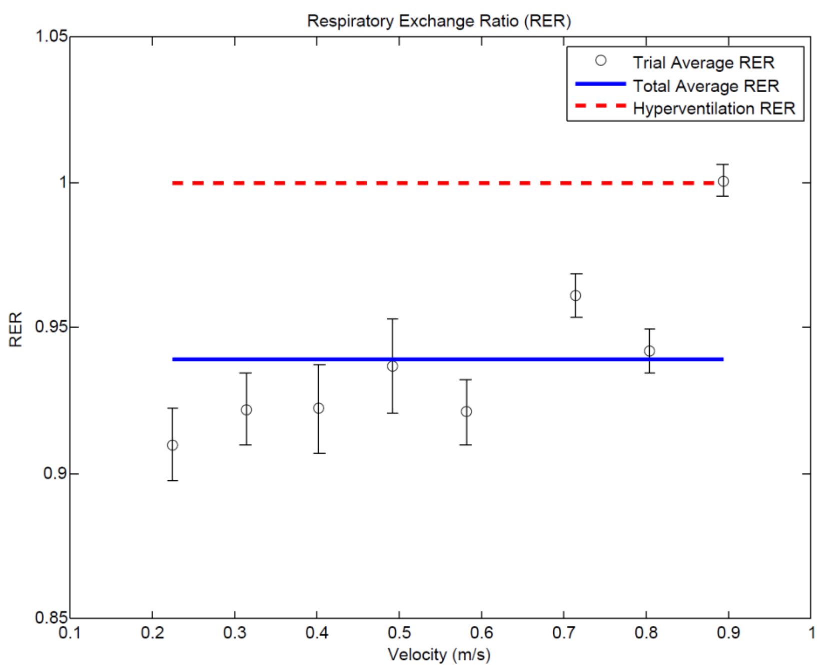

Figure 4: RER plot for treadmill testing for one subject

The second test used to determine the quality of the data was checking the linear relationship between ventilation and $\dot{V}_{O_2}$. Whenever, a person is not undergoing severe physical activity, these two variables should be approximately linear [8,9]. This test is used to look at the noise within the VO2 system itself. Displayed in Figure 5 is a sample plot of the ventilation ($\dot{V}_E$) versus $\dot{V}_{O_2}$ for one of the trials for Subject 1 with the R^2 value. From plots like this, it was determined that while the data was roughly linear, there was a strong influence of noise within the system.

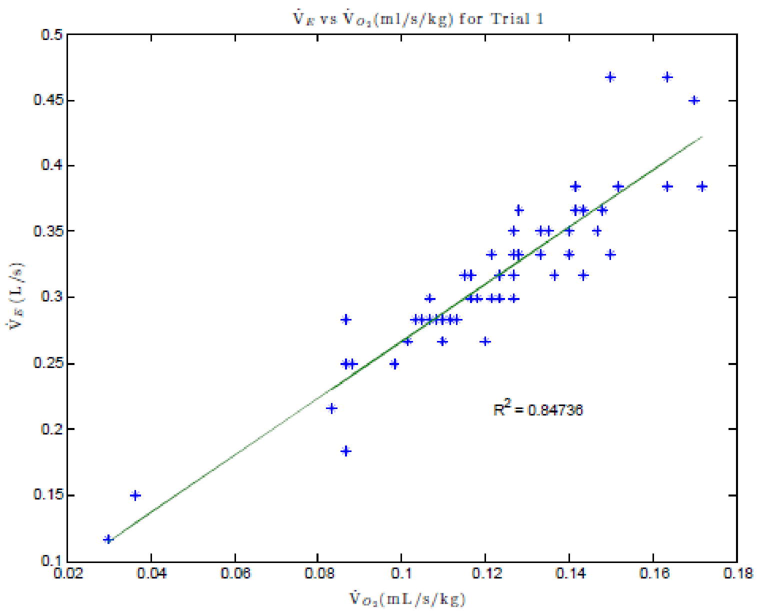

Figure 5: Data verification through a test for linearity between $\dot{V}_E$ and $\dot{V}_{O_2}$

The final test that was conducted on the raw data was to check for a normal distribution for each trial. To do this a normal probability plot was constructed for the $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ data for each trial. If the data followed the linear relationship, it could be considered to be normally distributed (or Gaussian). A sample plot of the normal probability is displayed in Figure 6. Like the sample shown, all of the plots displayed a linear relationship so the data could be considered Gaussian.

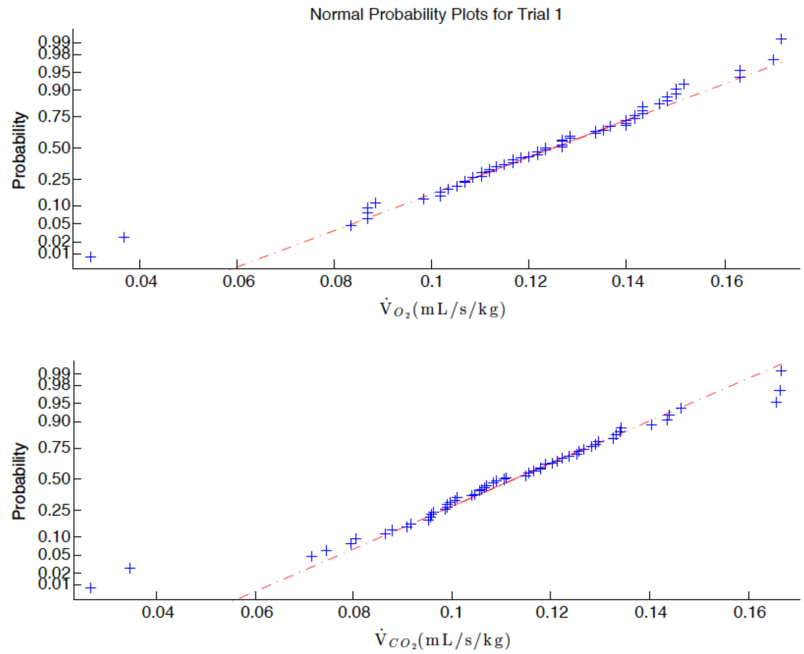

Figure 6: Check for normal distribution for trial 1. "Normal probability plot", linearity of the plots indicates normality of data

3.3 Individual Data Processing

The $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ data was used in conjunction with Equation 3 to find $\dot{E}_w$ for each breath. These values were then averaged over each trial to create one data point per velocity and then plotted against the square of the velocity. A best fit line was then constructed for each subject. A sample plot of this relationship is shown in Figure 7. The error bars in this plot display a 95% confidence interval, which assumes that the data has a Gaussian distribution and that each trial is independent of the others. Displayed in Table 3 are the equations for the best-fit lines for each subject and the corresponding R^2 value.

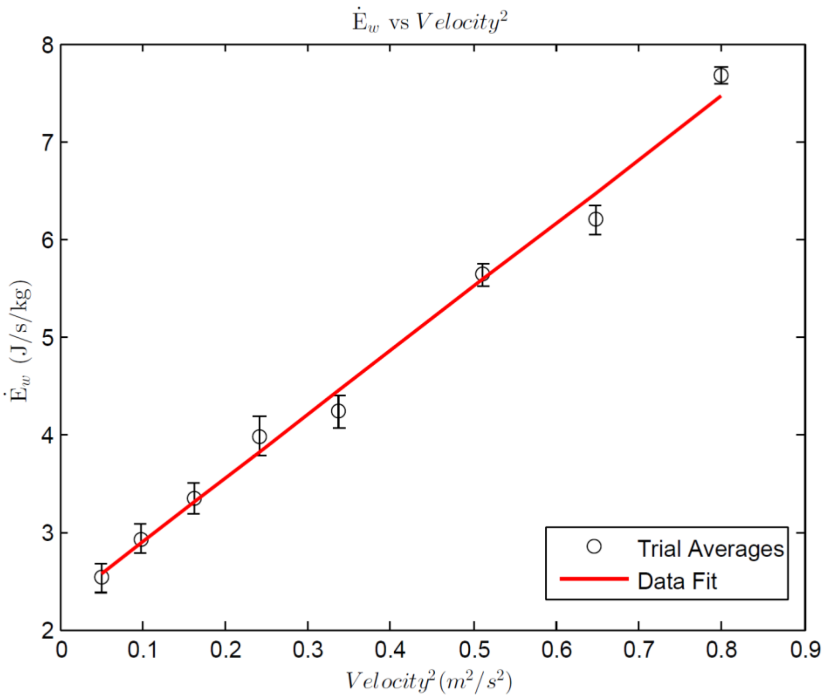

Figure 7: Linear relationship between $\dot{E}_w$ and v^2. Error bars display a 95% confidence interval.

Table 3: Linear fit equations for subject data

Subject #	v^2 Linear Fit	R^2 value
1	$\dot{E}_w = 7.37v^2 + 2.63$	0.9964
2	$\dot{E}_w = 6.74v^2 + 2.69$	0.9858
3	$\dot{E}_w = 6.53v^2 + 2.24$	0.9909
4	$\dot{E}_w = 7.07v^2 + 1.50$	0.9838
5	$\dot{E}_w = 8.87v^2 + 3.17$	0.9821
6	$\dot{E}_w = 7.55v^2 + 3.19$	0.9953

These equations can then be transformed so that they relate the energy per unit distance to the velocity simply by dividing the existing equations by the velocity. These new equations have a form similar to Equation 2 and contain a minimum value. This minimum was determined to be the Optimal Energy for this gait, which was located at the energy optimal speed. With these minima obtained, I could now compare them to the speeds found in the natural preferred speed testing. This comparison is shown in Table 4 for every test. Also shown in Figure 8 is a sample plot from Subject 3 of the energy optimal speed compared to the preferred natural speeds.

Table 4: Comparison of energy optimal and preferred speeds

Subject #	Energy Optimal Speed (m/s)	Initial Preferred Speed (m/s)	Speed Difference (m/s)	% Difference
1	0.597	0.687	0.090	14.99%
2	0.632	0.789	0.157	24.87%
3	0.586	0.626	0.040	6.82%
4	0.461	0.499	0.038	8.26%
5	0.598	0.397	-0.201	-33.56%
6	0.650	0.501	-0.149	-22.86%
Average Difference			**-0.004**	**-0.003%**
Average Absolute Difference			**0.112**	**18.56%**

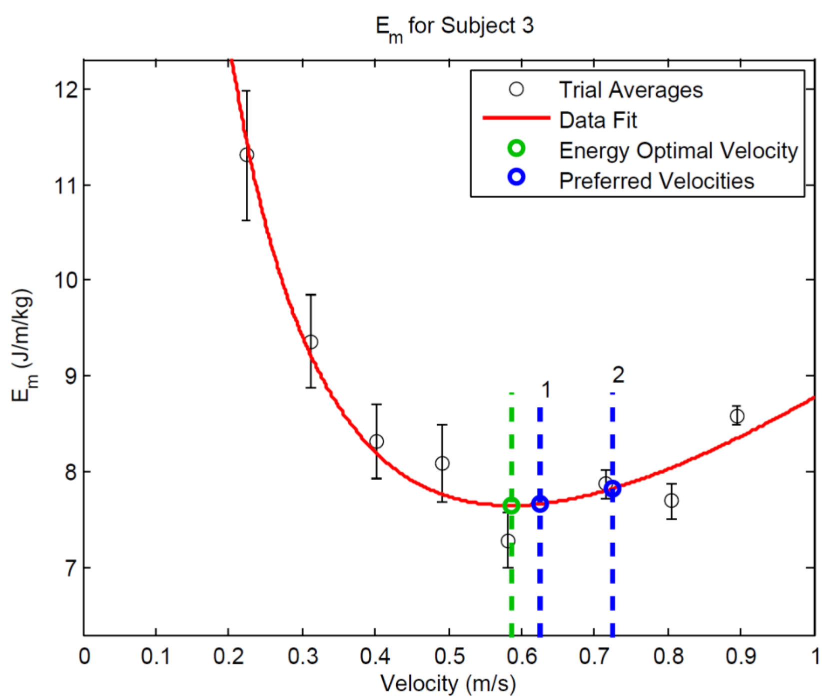

Figure 8: Sample plot of energy optimal values compared with preferred values. Initial preferred speed is labeled, 1 and post-treadmill preferred speed is labeled, 2.

3.3.1 Energy Optimal Velocity Robustness Check

Due to noise in the system and the small number of trials used for each of subjects, it was necessary to test the robustness of the minima found. One way to do this is through a test known as **Jackknifing** [10] in which a trial is removed from the data pool and the minimum is recalculated. If this causes a major shift in the energy optimal speed, this would indicate that the best fit function is very sensitive to any change in the data set, thus making claims based on the function less credible. This test was performed multiple times for each subject (one test per velocity trial). The Jackknife results can be seen in Figure 9 where each point describes the trial that was removed. The percent difference between the minima found for each subject and the minima found from Jackknifing can be seen in Table 5.

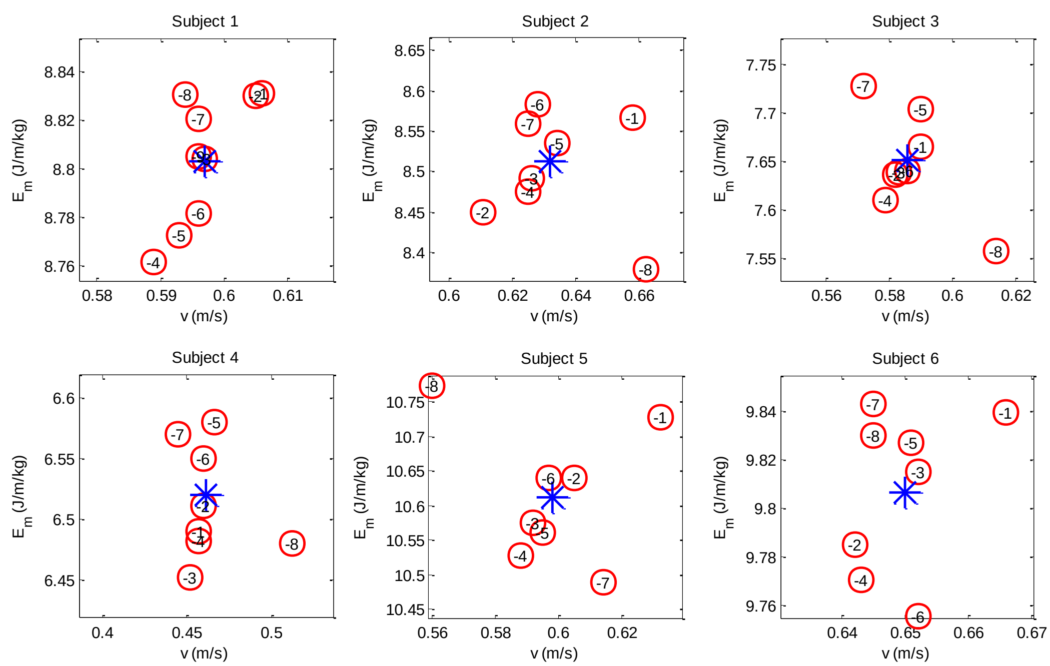

Figure 9: Jackknife results for each subject. The blue star displays the minimum found with all trials included and the red circles display the minimum found with the corresponding number trial subtracted (e.g. A circle with a -3 displays the minimum when trial 3 is removed). See also Table 4.

Table 5: Comparison of energy minima for each subject and those from jackknife tests

% Difference of Energy Optimal Speed and Jackknifed Energy Optimal Speed									
Subject #	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9
1	1.51%	1.34%	0.00%	1.34%	0.67%	0.17%	0.17%	0.50%	0.17%
2	4.11%	3.32%	0.95%	1.11%	0.32%	0.63%	1.11%	4.75%	n/a
3	0.68%	0.68%	0.51%	1.19%	0.68%	0.00%	2.39%	4.78%	n/a
4	0.87%	0.22%	1.95%	0.87%	1.08%	0.22%	3.47%	11.06%	n/a
5	5.69%	1.17%	1.00%	1.67%	0.50%	0.17%	2.68%	6.35%	n/a
6	2.46%	1.23%	0.31%	1.08%	0.15%	0.31%	0.77%	0.77%	n/a

These results show that for most subjects, removing any one trial will only change the energy optimal velocity by a very small amount. However, there are a few that appear to be more sensitive, particularly trial 8 of subject 4. This means that any change associated with that trial has a large impact on the location of the energy minimum.

3.4 Combined Data Processing

Along with all of the individual results, I also looked at the results of the population as a whole. By combining all of the data into one data set, I found an equation similar to Equation 2 found by Ralston that could describe the minimum energy speed associated with the entire population. Figure 10 and Figure 11 show the best fit line associated with the entire population and the minimum energy plot found from this function. The equations associated with these functions are shown as Equations 4 and 5. Also shown in each of the figures is the corresponding equation found in Ralston's study. As was predicted in the beginning of the experiment, each subject had a different energy and velocity relationship which caused the R^2 value to be 0.8446 rather than the R^2 values close to 1.0 found in the individual results.

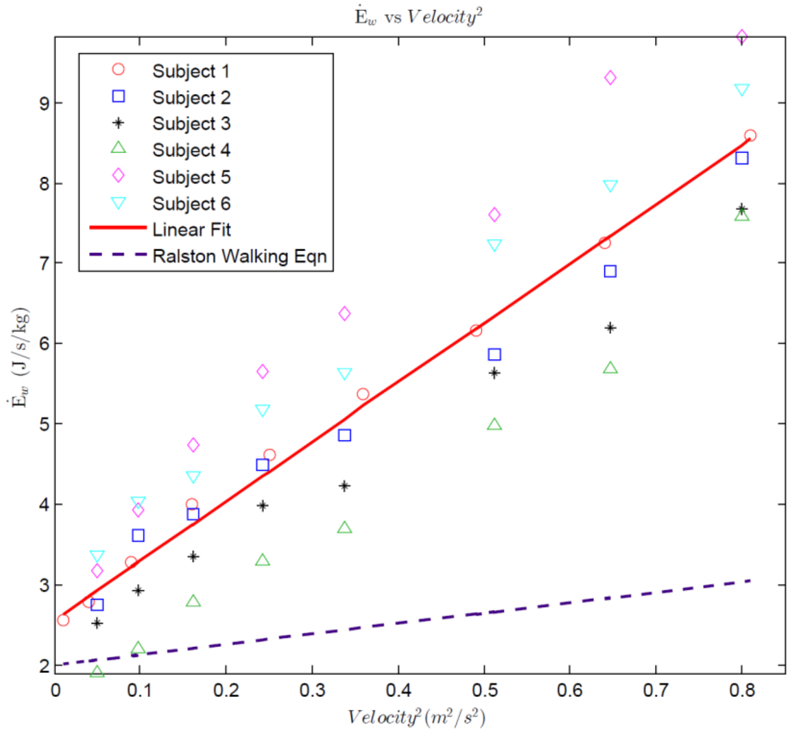

Figure 10: Linear fit of combined results of all subjects. Ralston's equation displayed as the dotted line.

$$\dot{E_w} = 2.573 + 7.349v^2 \;\; J/sec/kg \tag{4}$$

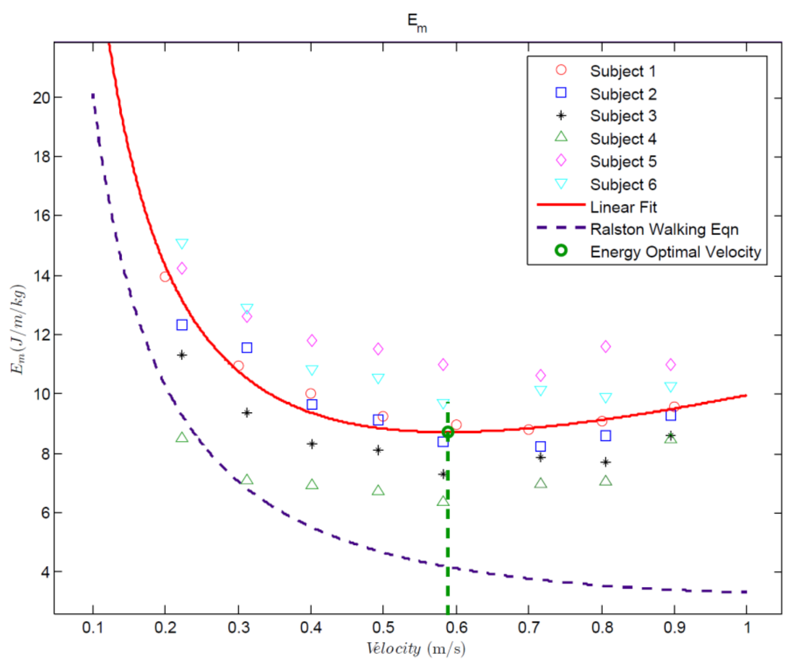

Figure 11: E_m plot with Energy Optimal velocity for combined results. Ralston's equation displayed as the dotted line.

$$E_m = \frac{2.573}{v} + 7.349v \ \ J/meter/kg \tag{5}$$

Just like in the individual results, the energy optimal speed was determined by finding the location of the optimal energy value associated with Equation 5. This speed was found to be 0.592 m/s and was then compared to the preferred velocities of each subject and the results are displayed in Table 6. This population energy optimal could also be compared to the energy optimal gait of each individual. The results of this comparison are shown in Table 7.

Table 6: Comparison of preferred speed to population energy optimal speed (0.592 m/s)

Subject #	Natural Preferred Speed (m/s)	Speed Difference (m/s)	% Difference From Population Energy Optimal Velocity
1	0.687	0.095	15.96%
2	0.789	0.197	33.30%
3	0.626	0.034	5.74%
4	0.499	-0.093	-15.70%
5	0.397	-0.195	-32.89%
6	0.501	-0.091	-15.30%
Average Difference		**-0.009**	**-1.5%**
Average Absolute Difference		**0.117**	**19.82%**

Table 7: Comparison of individual optimal speed to population optimal speed (0.592 m/s)

Subject #	Energy Optimal Speed (m/s)	Speed Difference (m/s)	% Difference From Population Energy Optimal Speed
1	0.597	0.005	0.84%
2	0.632	0.040	6.76%
3	0.586	-0.006	-1.01%
4	0.461	-0.131	-22.13%
5	0.598	0.006	1.01%
6	0.650	0.058	9.80%
Average Difference		**-0.047**	**-0.79%**
Average Absolute Difference		**0.041**	**6.93%**

4. Conclusions

4.1 Contributions

We found that the optimal speed across the population was 0.592 m/s with individual minimums differing by an average of 0.041 m/s, and the preferred speeds, averaging 0.583 m/s (standard deviation = 0.1437). However, because the variability across subjects is high, we found that each individual's energy optimal speed predicted their preferred speed by an average absolute error of 0.112 m/s (about 19%).

Another contribution is the measurement of energy costs for sideways walking, which we found to be much higher than normal walking, suggesting why we do not use sideways walking in daily life. Moreover, by comparing Equations (2) and (5) it can be seen that the energy optimal speed is predicted to be 0.592 m/s for shuffling and 1.2m/s for walking.

4.2 Discussion

The most significant source of error likely comes from the influence of other variables. One such variable is likely to be perceived velocity of the subject. This can be concluded by comparing the results of the two preferred speed tests. Without exception every subject increased in speed from the first hallway test to the second. As anyone who has tried walking after a long distance run, their natural pace seems incredibly slow since they have been moving at a fast pace for so long. This is a probable explanation for this change in preferred speeds because prior to the second test, each subject had been performing anywhere from 2 to 4 trials which were faster than their original preferred speed. Due to the lengths of each of these trials, this means that they were shuffling at an increased pace for 12-24 minutes. Other variables, which may have also affected the subjects' preferred speeds, could be muscle strength and prior experiences using a similar gait.

Along with this, I can conclude that despite the R^2 value of the best fit line for the population being much lower than those found for the individual results, the population energy minimum can still be a decent predictor of an individual's personal energy minimum. This claim can be made based on Table 7 which shows that 5 out of 6 of the subjects had less than a 10% difference between their personal energy optimal speed and that of the population. Also the average absolute percent difference between the subjects' personal optimal speed and the populations was only 6.93%. Therefore, this data suggests that a person's energy optimal sideways walking speed will be about 0.592 m/s with an average absolute error of 6.93%. This corresponds to an absolute error of just 0.041 m/s.

4.2 Additional Applications

This study only observed the velocity associated with a shuffle sideways gait. However, this testing procedure could have many other applications. One way it could be modified is by observing other variables for a sideways gait such as step-frequency. A test involving step frequency could produce results with less "conscious-thinking-induced" variability since most people are much more conscious of their speed than their step frequency. Because of this, the results of an experiment performed on step-frequency are more likely to depend solely on people's energy usage rather than their perception. This procedure also has applications for looking at variables of other gaits as well. One experiment in particular would be to compare the energy usage of different gaits associated with different types of prostheses [3].

4.3 Future Work

Even though there are many other applications for this particular procedure, there is still a large amount of information that needs to be studied from this experiment. First and foremost, I believe this experiment should be continued to accumulate a larger subject population in order to provide a stronger conclusion for this experiment. At the time of writing this document, only 6 participants were tested. With a larger population any similarities or differences that exist between subjects would become clearer. Also, in future tests, it would be useful to look at affects associated with reversing or randomizing the velocities for each subject. This could help remove some of the effect that perception had on the second hallway tests. Finally, I believe future subjects would benefit from completing the test on a larger treadmill. Most subjects during testing felt that the treadmill testing was confined and that they felt uneasy performing some of the higher speed tests.

Beyond continuing this experiment, it would be useful to look at follow up experiments that could test some of the results. One such experiment could be to look at how long it would take for a person to start using a gait consistent with their energy optimal. This is interesting because my experiment shows that the initial preferred speed is not necessarily the same as the energy optimal for a novel gait; however, Ralston's experiment shows a stronger correlation between the two for a natural walking gait. Based on these results, one may conclude that as a person becomes comfortable with a gait, they begin to use a speed that is closer to their energy optimal. A way to test this theory is to perform a long-term study where participants have their preferred speed tested daily and their energy optimal speed tested weekly. Then we can track the person data over the weeks to determine if the persons preferred speed approaches their energy optimal. This test would also show if the participants' energy versus velocity curves change over time.

4.4 Summary

This experiment set out to see if energy optimality could predict the gait of a person while they use an unnatural gait. Upon the completion of this experiment, we now have evidence that suggests that we can predict a person's preferred sideways walking speed as 0.592 m/s with about a 0.12 m/s average absolute error. This experiment also suggested that a person's speed is likely influenced by variables other than energy usage, and it is possible that this theory will be a more accurate predictor of other variables associated with the sideways gait such as step-frequency. So while it may not be possible to predict the exact gait of a person using a novel gait for the first time using this theory, it may still be possible to predict the subjects speed as the gait is used more often.

References

[1] H. Gray, “Anatomy of the human body,” Philadelphia: Lea & Febiger, 1918; Bartleby.com, 2000. www.bartleby.com/107/. (9/26/12).

[2] R. McN. Alexander, “Optimization and gaits in the locomotion of vertebrates,” Physiol. Rev. 69, 1199 . (1989).

[3] H. J. Ralston, “Energy-speed relation and optimal speed during level walking,” Eur. J. Appl. Physiol. 17, 277 (1958)

[4] J. M. Donelan, R. Kram, and A. D. Kuo, “Mechanical and metabolic determinants of the preferred step width in human walking,” Philos. Trans. R. Soc. London, Ser. B **268**, 1985 (2001).

[5] P. Högberg, “How do stride length and stride frequency influence the energy-output during running?” Arbeitsphysiologie **14**, 437 (1952).

[6] J. E. A. Bertram and A. Ruina, “Multiple walking speed-frequency relations are predicted by constrained optimization,” J. Theor. Biol. 209, 445(2001).

[7] J. M. Brockway. “Derivation of Formulae Used to Calculate Energy Expenditure in Man”. Human Nutrition: Clinical Nutrition, 41C:463-471, May 1987.

[8] T. J. Barstow, R. Casaburi, and K. Wasserman. “O2 Uptake Kinetics and the O2 Deficit as Related to Exercise Intensity and Blood Lactate”. Journal of Applied Physiology, 75(2):755-762, 1993.

[9] W. D. McArdle, F. I. Katch, and V. L. Katch. “Exercise Physiology: Nutrition, energy, and human performance.”. Lippincott Williams and Wilkins, 7th edition, 2010.

[10] Shao, J. and Tu, D. (1995). The Jackknife and Bootstrap. Springer-Verlag, Inc. pp. 281